Achieving Supportability on Exploration Missions with In-Space Servicing

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One of the long-term exploration goals of NASA is manned missions to Mars and other deep space robotic exploration. These missions would include sending astronauts along with scientific equipment to the surface of Mars for extended stay and returning the crew, science data and surface sample to Earth. In order to achieve this goal, multiple precursor missions are required that would launch the crew, crew habitats, return vehicles and destination systems into space. Some of these payloads would then rendezvous in space for the trip to Mars, while others would be sent directly to the Martian surface. To support such an ambitious mission architecture, NASA must reduce cost, simplify logistics, reuse and/or repurpose flight hardware, and minimize resources needed for refurbishment. In-space servicing is a means to achieving these goals. By designing a mission architecture that utilizes the concept of in-space servicing (robotic and manned), maximum supportability can be achieved.

Nomenclature

ARM	=	Asteroid Redirect Mission
ARRM	=	Asteroid Redirect Robotic Mission
ARV	=	Asteroid Redirect Vehicle
ATLAST	=	Advanced Technology Large Aperture Space Telescope
DARPA	=	Defense Advanced Research Projects Agency
DoF	=	Degrees of freedom
DxR	=	Dexterous robotics
EDU	=	Engineering development unit

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ENT	=	EVR Nozzle Tool
EVA	=	Extravehicular activity
GEO	=	Geosynchronous Earth orbit
GNFIR	=	Goddard Natural Frequency Image Recognition
GSFC	=	Goddard Space Flight Center
FDV	=	Fill/Drain Valve
HST	=	Hubble Space Telescope
ISS	=	International Space Station
KSC	=	Kennedy Space Center
LEO	=	Low Earth orbit
MDP	=	Maximum design pressure
MFT	=	Multifunction Tool
QD	=	Quick Disconnect
RROxiTT	=	Remote Robotic Oxidizer Transfer Test
RPO	=	Rendezvous and proximity operations
SSCO	=	Satellite Servicing Capabilities Office
SCT	=	Safety Cap Tool
SEP	=	Solar electric propulsion
STC	=	Servicing Technology Center
TCA	=	Tertiary Cap Adapter
TRL	=	Technology Readiness Level
WCT	=	Wire Cutter and Blanket Manipulation Tool
XTS	=	Xenon transfer subsystem

I. Introduction

NASA's Satellite Servicing Capabilities Office (SSCO) at the Goddard Space Flight Center (GSFC) is consistently advancing the Technology Readiness Level (TRL) of several key technologies required for future missions to utilize in-space servicing. In particular, through demonstrations on the ground and the International Space Station (ISS), SSCO is advancing three critical technologies that would enable supportability: rendezvous and proximity operations, robotic tools, and fluid transfer.

Utilizing in-space servicing capabilities is critical for future exploration missions to achieve supportability. The ability to refuel various propellants of future exploration vehicles in space would allow those vehicles to be reused and/or repurposed multiple times without returning them to Earth. Fully autonomous rendezvous and proximity operations systems are another enabling technology for a mission to Mars. All multilaunch mission architectures—crew vehicle, habitat module, transfer vehicle, surface lander—will require the mating of separate flight components together in Earth, Lunar, and Martian orbits. Since NASA can control both sides of the mating interface, these docking events can be simplified using the many cooperative interfaces—such as communication and ranging cross-links, cooperative navigation targets, and common berthing and docking standards—all currently in development by SSCO and others. And whether the goal is refueling, rendezvous, or another venture, advanced robotic tools would be required. Tools that can connect to a fill and drain valve, grasp a spacecraft, manipulate hoses and cables or do any number of other tasks would provide versatility to a robotic servicer being commanded either locally in space, remotely from Earth, or autonomously.

Planners of future exploration missions can take advantage of NASA's current TRL advancements in servicing technologies to reduce cost risk, boost supportability, and ultimately improve mission success.

II. In-Space Servicing Technologies

A. Argon

To obtain robust servicing capabilities, one must first start with the underlying necessary technologies. To achieve fully autonomous rendezvous and docking (with no human in the loop), multiwave length sensors, advanced algorithms, and a high-speed, radiation tolerant computing platform must all be matured as a system.

Argon was a system developed for a ground demonstration to mature capabilities in support of Rendezvous and Proximity Operations (RPO) required to service a non-cooperative spacecraft.[1] Objectives of the test campaign included advancing sensor algorithms, evaluating candidate algorithms, and and performing side-by-side

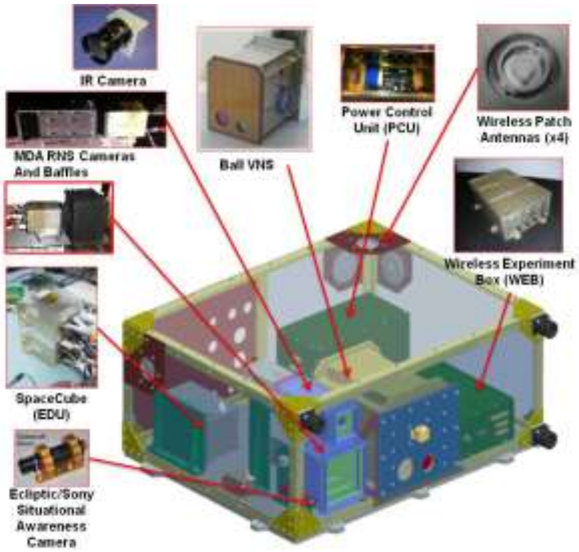

Figure 1. Argon components. *The Argon system included several components to test different algorithms, sensors, and autonomous rendezvous capabilities.*

performance of comparable sensors. The suite of sensors on Argon is being tested for use with RPO that could bring a servicing satellite from a range of 100 meters to 2 meters of a spacecraft. During this period, six degree of freedom (DOF) pose information is required. This information must be quickly relayed from the RPO to the robotic system in order to achieve capture. Because performing such an operation would be almost impossible with humans in the loop due to latency, development of these sensors and algorithms is critical to creating a mission based around a servicing architecture.

The Argon system tested three algorithms for the purposes described above. Goddard Natural Frequency Image Recognition (GNFIR) uses visual information from the camera to extract features of the mock client. These features are then matched to a model preloaded into the software. This algorithm was also tested on STS-125 as an experimental payload[2]. On that mission, the software was used to track the Hubble Space Telescope (HST) as the Space Shuttle Atlantis rendezvoused with the telescope. On Argon, a full-scale model of the GOES-12 aft bulkhead (the subject of an early design reference mission for satellite servicing) was built and placed in the client range of the Argon system. The Argon version of GNFIR was advanced in many ways over the version that flew on STS-125. In addition to GNFIR, Argon hosted the GSFC FlashPose algorithm, which processes real-time flash LIDAR frames to produce a 6-DOF pose estimate. The final algorithm tested on Argon was the Johnson Space Center 3D Pose. These algorithms used retro-reflectors to determine pose data of the mock client spacecraft.

Argon was tested in multiple labs with a variety of configurations and initial conditions. At GSFC, the SSCO robotic test facility allowed testing with robotic systems. In a large integration facility at GSFC, testing could be conducted that allowed distances between Argon and its target of up to 90 meters. And in the Proximity Operations Test bed (POTS) at the Naval Research Laboratory, the system was integrated with 6-DOF motion platforms that allow closed-loop system testing from separations of 20m or more to the point of capture. The Argon test campaign was very successful and provided engineers developing RPO technologies knowledge of how to develop a system for a future mission.

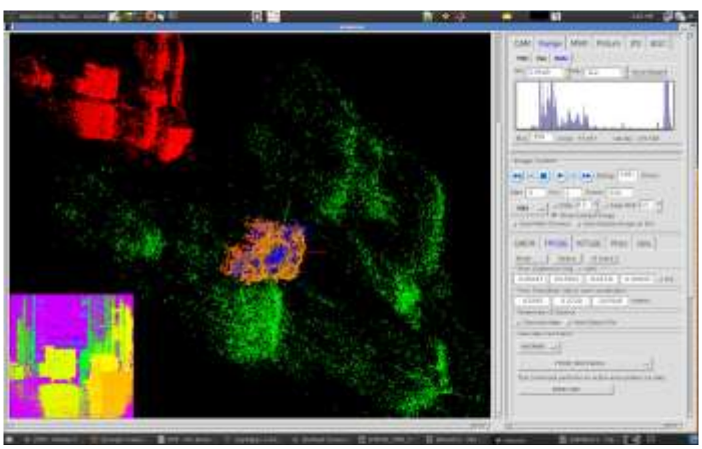

Figure 2. FlashPose visual processing. *A screenshot of the Flashpose algorithm processing a range image of the GOES-12 mockup used in Argon testing.*

B. Raven

Raven is an ISS experiment being launched in 2016 aboard the Space Test Program-Houston 5 (STP-H5) payload that builds upon the work done for the Argon project. The experiment will demonstrate the next-generation sensors, vision processing algorithms, and high-speed, space-rated avionics of an autonomous navigation system.[3] By focusing its sensors on incoming visiting vehicles to ISS, Raven will be able to perform real-time calculations of relative navigation data with on-orbit assets, which will verify RPO sensors and algorithms that are planned for use in satellite servicing and other future missions by NASA. The need for this technology was established by NASA in 2014 as part of an assessment of proposed missions and documented in the 2014 Asteroid Redirect Mission (ARM) Broad Agency Announcement.

Figure 3. Argon in test. *The Argon system is mounted to a dolly and placed in range of the GOES-12 model during the test campaign at GSFC.*

Raven's objectives are to provide an orbital test bed for relative navigation algorithms and sensors, to demonstrate multiple rendezvous paradigms can be accomplished with a similar hardware suite, and to demonstrate an independent visiting vehicle capability. At SSCO, the goal is to develop and mature technologies that are required for satellite servicing missions. Raven will provide on-orbit experience for SSCO engineers that will validate some of the developments made thus far in RPO sensors and algorithms. In addition, the work done for satellite servicing has applications to other missions, notably the proposed Asteroid Redirect Mission. By verifying algorithms better suited to those missions also function with the hardware on Raven, NASA will have developed a resource that can be applied for multiple purposes, which reduces non-recurring engineering costs for the agency. Finally, Raven will serve as an asset to ISS. Currently, no relative navigation information on visiting vehicles is assessed by NASA – all data for the crew and ground operators is relayed from the visiting vehicle. Raven will provide the capability for NASA to gather that data, and perhaps eventually eliminate the need for it to be on the visiting vehicle, which may be disposed of after each mission.

STP-H5 will be installed on the inboard, nadir side of ELC-1, giving Raven a prime spot for observing visiting vehicles. Raven will begin to track the vehicles at a distance of 1km and continue tracking them until docking or berthing at a distance of 20m. Once commanded to begin tracking a vehicle from the ground, the gimbal onboard will autonomously keep the sensors pointed toward the visiting vehicle. There are numerous methods under which Raven can operate. As more and more visiting vehicles are tracked and operators on the ground are able to improve the algorithms, the process will become more autonomous. Even when not tracking visiting vehicles, Raven can be used by ISS to provide additional camera views, test out vision algorithms, and collect data on the vibration environment onboard ISS.

Raven will provide an on-orbit test bed to NASA for developing the algorithms necessary to conduct RPO on any future missions where two spacecraft must dock, and human-in-the-loop control is either

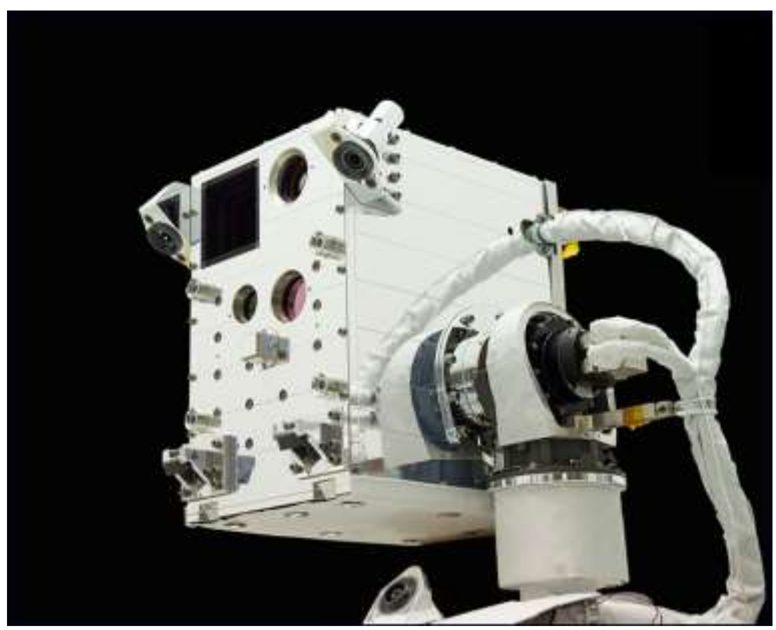

Figure 4. Raven payload. *A picture of the Raven payload fully integrated for flight.*

not possible or not practical. As a result, TRLs for these technologies will be raised to a level of 6 or above.

C. Robotic Refueling Mission

The Robotic Refueling Mission (RRM) (see Figure 5) was launched in July 2011 aboard STS-135 to the International Space Station (ISS). RRM had multiple objectives, but the primary task was to demonstrate refueling of a typical satellite hypergolic propulsion system fill drain valve (FDV) by doing an end-to-end demonstration that involved removing the caps on the outside of the valve and connecting to it for a fluid transfer with a simulant propellant. To do this, RRM included four robotic tools that the ISS on-orbit robotic system known as the Special Purpose Dexterous Manipulator (SPDM) or 'Dextre' could pickup and utilize to perform the tasks required to access

Figure 5. Robotic Refueling Mission payload. *During final preparations for launch, the RRM payload installed on the carrier that would take it to orbit in the Space Shuttle Atlantis cargo bay.*

and connect to the valve. The tools are as follows, one, the Wire Cutter and Blanket Manipulation Tool (WCT), two, the Multifunction Tool (MFT), three, the Safety Cap Tool (SCT), and four, the EVR Nozzle Tool (ENT). All RRM operations were commanded from the ground.

The WCT (see Figure 6) was used to cut the small wires tightly installed on the ground to tie safety caps to the valve. On a typical satellite, these wires are installed on the ground following propellant servicing. They are not designed to be removed, as existing satellites are built without the expectation of on-orbit refueling.

Figure 6. Wire Cutter Tool. *The RRM Wire Cutter Tool is used to cut one of the wires of the fill and drain valve mounted to RRM. This is a screenshot from the video captured by the tool's cameras during the operations.*

In total there were three wires on the FDV: one that tied the Tertiary Cap to the valve body, one that tied the Safety Cap to the valve body, and one that tied the Actuation Nut to the valve body. On RRM, operators on the ground were able to successfully use the Wire Cutter Tool to cut these wires by commanding a small amount

of torque through an innovative blade advance mechanism while using the wire snare feature on the rear side of the tool tip to capture and restrain the wire during the cutting operation. In addition, the tool had a unique prying feature on the front of the tool tip for manipulating the wire into a favorable position for cutting. Cutting the wire was the preferred method of breaking the wire in order to control the area of the break as well as the potential for debris. An alternative concept was tested in the development of RRM, which involved grasping the different caps and simply torqueing them until the wires snapped. However, this process could have created debris because the wires might have broken in an unpredictable location. Because the ISS is a manned spacecraft, its payloads are highly discouraged from doing anything to create debris that could interfere with life support systems. By cutting the wires precisely in a controlled process, no debris was created.

Figure 7. Multifunction Tool. *The RRM Multifunction Tool is used to remove the tertiary cap from the fill and drain valve mounted to RRM. This fill and drain valve is typical of those valves found on most satellites on-orbit.*

The MFT was designed to perform multiple duties due to the fact that it has a standard interface that can manipulate unique tool adapters. Four adapters were built for RRM that had a wide range of capabilities. Because these adapters could be changed out on-orbit, only one tool was required to perform multiple tasks. This capability allowed additional tasks to be planned for RRM with a minimal impact to the overall mass of the payload. For the purpose of removing the tertiary cap from the FDV, the MFT was equipped with a Tertiary Cap Adapter (TCA) (see Figure 7). Once operators used the tool to acquire the cap, it was unthreaded and removed from the valve. The adapter was designed to capture the valve and prevent it from floating away and becoming debris.

Alignment marks were placed on the adapter so that it could be placed into a start position that was the same as the start position the tool was in on the ground when the operators would practice the task. Because the valve was never meant to be serviced on-orbit, the operators used overlays on the downlink video to position the alignment marks with features on the valve and cap (e.g. a screw head or machined edge). Once the position of the adapter was known to be aligned with the cap, the commands required to have the SPDM move the tool onto the valve and capture and remove it were executed without any issues.

The SCT was used next to remove the inner cap covering the valve (seen in Figure 6). This tool used the same method for acquiring and capturing the cap as the TCA, which also allowed operators to turn the cap, unthread, and remove it fully captured. This left the valve exposed for the refueling tool.

Figure 8. EVR Nozzle Tool. *The RRM EVR Nozzle Tool is connected and to the RRM fill and drain valve. The tool was used to open the valve and provide a leak-free seal for transferring fluid across the interface.*

The ENT (see Figure 8) served multiple functions. It was designed to connect onto the valve and open it by turning the actuation nut on the valve body. Once opened, fluid could be transferred across the interface. The tool included special features that would form a leak-free seal around the threaded portion of the valve body as it was installed. In addition, the part of the tool that threaded onto the valve (known as a 'Quick Disconnect') was removable, meaning the same tool could be used on a similar valve with a different thread size if equipped with a different Quick Disconnect (QD). Attached to the body of the tool was a hose, the other end of which went back to the fluid transfer system inside the RRM structure. When the tool was attached to the valve, a flow loop was created that ground operators could then command fluid inside RRM (ethanol was used) to pass through the tool, through the valve,

and back into RRM.

While other in-space fluid transfer demonstrations have been done before RRM (most notably with the Orbital Express mission in 2007), RRM was the first mission that demonstrated the capability for robotic systems in-space to operate on interfaces which were only designed for human operation on the ground. While future exploration missions would likely use cooperative interfaces designed for robotic operation, RRM advanced technologies in the area of robotic tools and provided an experience base for ground robotic operators on how to perform complex robotic tasks remotely. Even though the SPDM was not originally designed for such tasks, the SSCO team was able to design innovative tools to take advantage of the capabilities the robot did have. On future missions, robotic systems may be launched years before a specific servicing mission is envisioned. Therefore, tool engineers must be capable of working with existing hardware in-space if supportability is to be achieved, and the RRM project showed this could be done. Robotic Tools that can cut wire, remove caps, and refuel spacecraft may all be required for future missions. Because of RRM and subsequent missions such as RRM Phase 2 and RRM3, these technologies are being raised from a TRL1 to TRL6.

Figure 9. Cryogen Coupler Adapter. *Early concept design for the CCA.*

Robotic Refueling Mission 3 (RRM3) is a follow-on demonstration to RRM that is currently in development by the SSCO at GSFC. Like the original RRM module, it is being designed to take advantage of the ISS onboard robotic system, SPDM. Also like RRM, this new payload will focus on further spiral development of technologies for in-space fluid transfer. It will include fluids that spacecraft currently use and will use in the future – gaseous xenon and liquid methane – and include hardware for transferring these fluids in space.

One of the ways liquid methane will be transferred is through a newly designed cryogen coupler. The coupler is being designed in response to the need for a quick-disconnect style device that can be used by either robotic systems or humans on lunar and/or Martian surfaces. Liquid cryogens have multiple uses in space exploration, they can be used as propellant, coolant, or stored as an expendable human resource. The ability to refill the systems that utilize these fluids will allow the systems to be used over and over again. For this concept to become a reality, the interface between the supply tank and the system must be capable of multiple cycles and be easily actuated. The RRM3 Cryogen Coupler Adapter (CCA) (see Figure 9) will accomplish both these goals.

One design option is to use a bayonet design similar to one used previously on HST servicing mission tools. This design would allow either a robot or human to easily connect and disconnect the coupler from the coupler receptacle. Aside from mechanical actuation, the coupler must also allow the flow of liquid cryogen without allowing the cryogen to absorb heat and over-pressurize. While this version of the design includes an interface for an RRM robotic tool, a simple change to the design would allow it to feature an EVA knob for astronaut use. Because the coupler will require less than a full turn for engagement, it is well within the capabilities of a human hand motion without requiring any additional tools. Another type of transfer technology planned to be demonstrated onboard the RRM3 will be for high-pressure xenon commonly found in Solar Electric Propulsion (SEP) systems. Current concepts for future exploration missions to Mars and beyond are relying on the efficiency found in SEP systems to reduce mass as a result of the much higher specific impulse inherent in SEP. By refueling these systems in-space, these exploration vehicles can become even more efficient, last longer, and travel further. In order for a mission architecture featuring in-space servicing to become feasible,

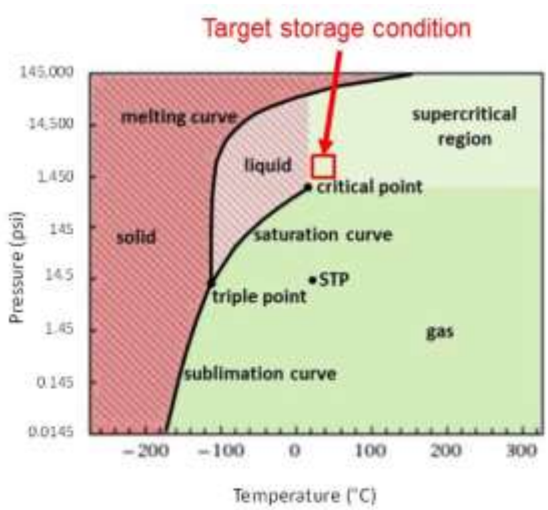

Figure 10. Xenon phase diagram. *This phase diagram for xenon shows the high pressure and temperature envelope that the supercritical phase SEP systems rely on for maximum storage efficiency.*

the servicing vehicle must also be capable of a high-efficiency transfer and be designed with reusability in mind. To that end, the concept being tested on RRM3 is one in which a pumping device is used to move the xenon from a supply tank to a receiver tank, instead of relying on pressure or temperature differentials to create conditions that would allow the xenon to move. This concept can also be scaled up to service larger spacecraft. More and more supply tanks can simply be connected to the same pump technology to increase the servicer's capability without having to change the dynamics under which the concept was developed.

One of the major challenges to developing this type of system include high-pressure transfer in the optimum mass/volume supercritical region for xenon (See Figure 10) while at the same time keeping subsystem design elements within their thermal limits in a reasonable transfer timeline. Proving the capability of these components to operate within specific target envelope pressures and temperatures is one of the objectives of the demonstration. In order to demonstrate scalable servicing concepts applicable to a large spacecraft while keeping within the limits required of ISS payloads, the Xenon Transfer Subsystem (XTS) on RRM3 will consist of two modules (the 'Fixed Module' and 'Robotic Module'). The Fixed Module will simulate the client spacecraft and include the receiver tank and female half of the transfer coupler. The Robotic Module will simulate the servicing spacecraft and include the supply tank, transfer device, and male half of the transfer coupler. The SPDM on ISS is planned to be used to align and mate the Robotic Module to the Fixed Module. During that docking process, the transfer coupler halves will be mated allowing operators on the ground to command the fluid system and pump fluid.

In 2014 and 2015, a team at the Kennedy Space Center (KSC) working in collaboration with SSCO executed a test campaign that involved setting up a system for performing xenon transfers using a variety of different ~~pumps~~ technologies to determine which kind of pump might be best for flight development.. Figure 11 shows one variation of the lab setup for these tests. Other data taken during the testing, such as pressures and controlled temperatures of fluid and components, while setting variables like pump speed and source xenon pressures, allowed a large collection of data to be taken that can be used in the design of the hardware for RRM3 and future missions.

Engineering Development Unit (EDU) Phase 1 Testing was completed in November 2014. This involved the test of a one-stage pneumatic pump to a system Maximum Design Pressure (MDP) of 1500 psig. The test was run at various pump speeds and achieved a 98-99% xenon mass transfer efficiency.

EDU Phase 2 Testing was completed in May 2015 and involved testing a two-stage electric pump to a system MDP of 2000 psig. The test again varied the pumping speeds, but this time the starting "client tank" pressure was also varied. A xenon mass transfer efficiency of nearly 100% was achieved.

A second round of Phase 2 Testing is currently underway (expected completion in July 2015) that involves repeating the initial round with the two tanks contained in water baths to pre-soak them to different potential on-orbit temperatures in order to anchor worst-case thermal models. The data from this testing is expected to help refine the thermal design used for the RRM3 hardware.

In all testing, commercial-off-the-shelf pumps are being used which would not meet the rigorous flight qualification requirements (e.g. shock, vibration, pressure) but do meet the basic functional requirements required for flight (e.g. flow rate, discharge pressure). In 2015, NASA released a Request for Information to gather data from

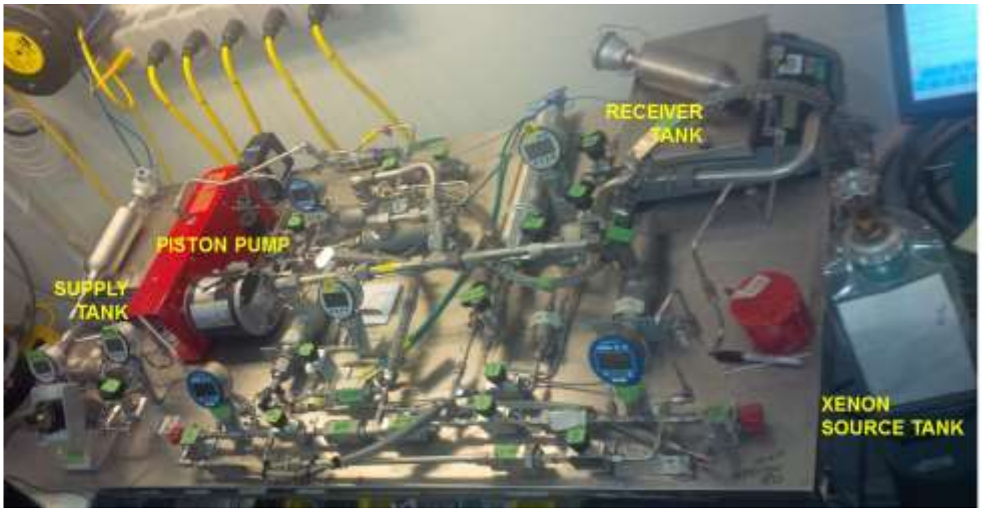

Figure 11. EDU Benchtop Test Setup. *This setup at KSC allowed engineers to monitor multiple points in the transfer flow and easily control different variables of the test to gather more data.*

industry about what pumps may be available for spaceflight.

The information received from those responses to NASA confirms the findings from the development testing. The optimum flight transfer device (presently at a low TRL) will utilize a multi-stage device that is applicable to target operating ranges and is scalable for larger missions. Additional stages can be added as required to enhance transfer timelines.

Future near term prototype testing with more flight-like systems will further refine the RRM3 XTS downselected design and determine the extensibility for use on exploration missions, such as ARM. One focus for this additional near-term ground system level testing will be to validate the thermal conditioning models of supply and receiver tanks and by limiting their ability to act as a heat sink and control xenon temperatures in a more flight like controlled simulation. Composite tanks are being considered on RRM3 in flight demo to show a better direct correlation and true extensibility to ARM due to thermal concerns with greatly reduced mass versus all-metal tanks.

The development testing, combined with the on-orbit demonstration on RRM3 of the xenon transfer pumping device, will raise its TRL from a 2/3 to a 6. This advancement will position it as a xenon transfer technology and operations concepts that can be incorporated into NASA's future missions with little-to-no risk to cost, schedule, or reliability.

D. On-Orbit Hypergolic Servicing Development (TRL advancements)

Hundreds of existing government and commercial satellite potential clients can be sustained into extended operational life or be utilized for repurposed missions if an on-orbit refueling capability of hypergol main Attitude Control Systems is developed and demonstrated on-orbit. Even with the trend towards electric propulsion systems for commercial and government long distance transfer, many new proposed missions such as ARM will also still require supplemental hypergol Attitude Control Systems for Rendezvous and Proximity Operations (RPO) maneuvers and other critical high-thrust maneuvers.

Major early risk reduction design, analysis, and testing for Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO) propellant transfer system EDUs have been completed by SSCO in collaboration with KSC engineering. Architecture concepts have been developed for refueling single and multiple clients with fuels and oxidizers (e.g. N2H4, MMH, and/or NTO). System analysis models have been made to determine transfer timelines and include thermal loading impacts. Low TRL component development progress continues on a seal-less pumping mechanism, high accuracy flow mass measurement, and vent dispersion modeling.

Early risk reduction development efforts were started in December 2011 with seal-less hypergol pump flight development and has progressively worked to achieve major risk reduction in overall system level test and analysis, plus further testing to flight like conditions and environments. Typical efforts involve component level development and testing of low TRL items followed by reference fluid then hypergol integrated system testing approach to validate the designs and test articles. The team has also taken advantage of historical reliability and risk studies and testing from past hypergol programs.

Over thousands of initial component level and partial propellant servicing system test runs were completed on the proposed refueling concepts, starting with simulant fluids, prior to them completing with hypergols. The most significant integrated system risk reduction test completed to date involved a ground demonstration at KSC called the Remote Robotic Oxidizer Transfer Test (RROxiTT) (seen in Figure 12), which transferred a hypergolic liquid oxidizer through an advanced Propellant Transfer Subsystem (PTS) into a satellite mockup at client pressures and flowrates. This operation included a seal-less Transfer Hose Assembly, specially designed for use on a robotic servicer, which connected the PTS to an Oxidizer Nozzle Tool and Quick Disconnect at the end of a robotic arm that was mated to the client fill-drain valve. The robot system utilized was remotely controlled by an operator at GSFC, 800 miles distant, to simulate the effect of an operator on the ground controlling a system in space, including control delay times.

Integrated testing of the four primary fluid components of the EDU PTA was intended to highlight any non-compatibility of the individual hardware systems when operated in concert. The four primary components under test are the pump device, fluid management, accumulator, and nozzle tool. Other fluid and electrical components were added to the test assembly to replicate satellite fluid system components. System properties that were simulated included pressure drop, layout, and valve timing. Mechanical simulators or test article hardware was used to supply, transport, temperature control and measure the properties of the simulant and actual fluids. Electrical simulators or test sensors and controllers were used to measure and record temperatures, pressures, forces, currents, and voltages. Components used in place of flight hardware were modified as needed to best replicate the components they were intended to simulate as well as provide as close a facsimile of the flight conditions as the test can achieve.

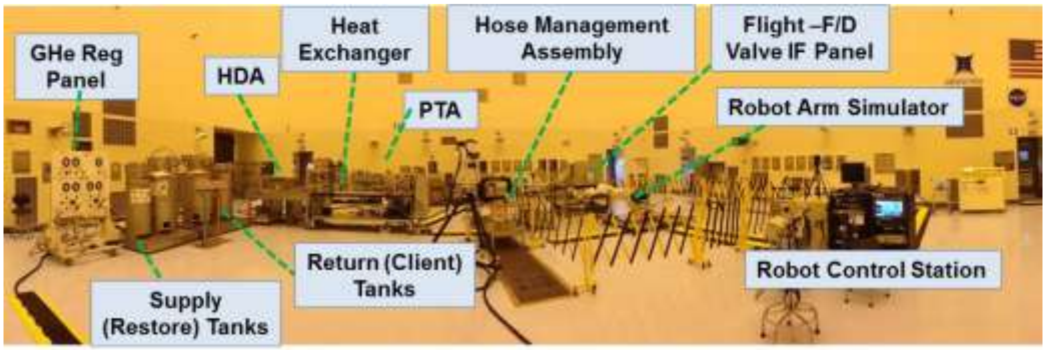

Figure 12. RROxiTT remote robotic hypergol fueling demo/testing at KSC (February 2014).

The bellows accumulator integrated testing objective was to characterize both the mechanical and electrical performance of the assembly as part of a satellite based fluid transfer system. The test allowed the team to perform flight system, operation concepts and controls validation. This included providing functional data to prove and advance current flight system design. Empirical (validation) data to flight system analysis was created. Testing also advanced the TRL of several technologies per Table 2.

The test also allowed engineers to quantify pressure drop and component leakage in the refueling tool, including the Quick Disconnect (QD), QD poppet with different seal configurations, and fill and drain valve.

CONOPS trade testing and validation was another objective. Pump startup and shutdown modes with various client and PTA configurations were tested as well as transfer modes with constant and varying pump speeds. Validation occurred with different simulated transfers such as those developed for refueling typical government-owned LEO spacecraft. Other modes were validated during the testing as well, including pump failure, purging of liquid downstream of the PTA outlet valve, and client fill using only a bellows.

Several conclusions were reached as a result of the testing. All listed primary and secondary test objectives were met, and data learned is being utilized for final flight design decisions. The flight-like components (pumps, flow meter, and bellows) function well together in the most extreme operating client transfer conditions. The ultrasonic flow meter did not perform as advertised to accuracy levels by the vendor with relevant fluids. Coriolis flow meters were the only device that was able to achieve the accuracy goal. The pump startup and shutdown modes evolved significantly as the test team learned how the system responds to the various startup and shutdown conditions. The Ti bellows –accumulator performed its key and backup functions quite well.

Optimization for design and development of the specific type of PTS system to be used with specific LEO or GEO clients can now be made from a decision tool in-work to select best value for key parameters such as types of commodities, number of clients, client type, quantities required of specific propellants, transfer pressures required, allowable transfer timeline, remaining onboard propellant, client instrumentation/controls available, etc. Building planned servicing into an advanced mission architecture such as manned missions to Mars or ARM minimizes logistics and operations, minimizes maintenance complexity, and allows the re-use and re-purposing of flight hardware. Incorporating upfront supportability features such as fill drain valves with internal in-line and external secondary seals, accessibility of FDV for servicing including removable and reusable insulation covers, FDV heater power, labels, marking, or contrasting colors for image recognition, instrument feedback of strategic client temperature and pressures, and type or ratings of client propellant tanks with minimal cost and weight impact, increases the efficiency, potential useful life span, and flexibility of CONOPS for these NASA programs and assets.

III. Creating Supportability in Space Logistics with In-Space Servicing

In more than 50 years of human space exploration, human presence beyond LEO has been limited to a handful of very short duration missions to the lunar surface, the Apollo missions. Robotic presence has extended further out, to the surface of Mars. This effort has been highlighted by the Spirit and Oppurtunity rovers. Numerous probes to gather additional information on the solar system have been sent out to the sun, other planets and their moons, and asteroids. While the amount of data gathered by these missions is immense, there is even more knowledge that can be obtained with an expanded presence. That presence could be expanded by sending humans beyond LEO and the Moon to Mars, and by sending robots beyond Mars to the asteroid belt and to the moons of the gas giants. These goals have been discussed for decades, but ultimately have not been achieved because the complexity of such missions was deemed to be too high and too expensive. In order to increase the chances of making these visions a reality, these missions could be simplified and made cheaper. In-space servicing is a means to that end.

There are multiple missions detailed in Figure 13 below that would be required to transport humans to Mars. The technologies being developed for in-space servicing can aid in simplifying such a complex operation.

At multiple points in the above chart, rendezvous between spacecraft will be required. This could be accomplished with humans controlling the spacecraft in real-time, but this concept increases the resources required for each of those operations. Autonomous rendezvous sensors and algorithms being developed by SSCO on the Raven payload can remove the requirement for humans to be in the loop of those operations, which means they can

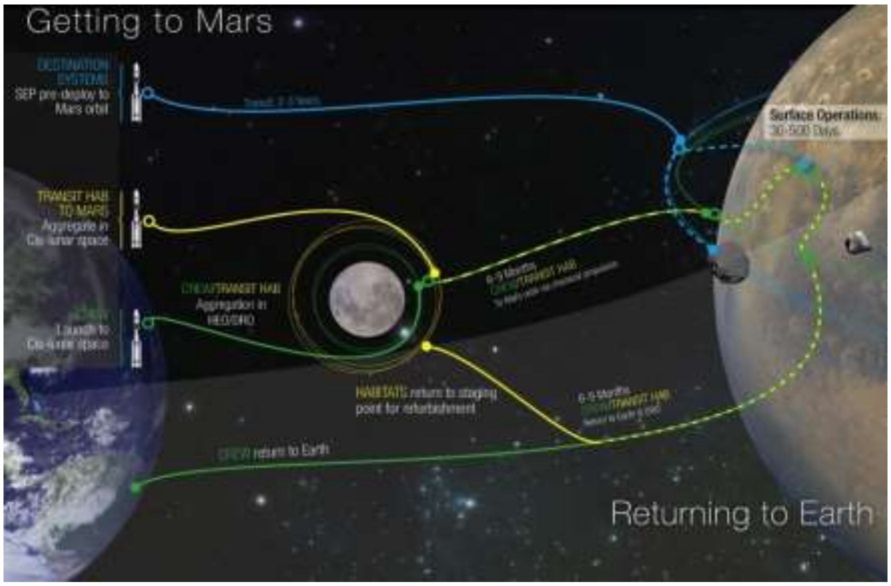

Figure 13. NASA conceptual diagrams for missions to Mars.

be done more often and with less resources. It reduces the training astronauts would be required to go through, which allows them to spend more time training to perform science activities that cannot be performed robotically.

The distance required for astronauts to travel in space to get to Mars is immense. The Apollo astronauts had to travel for days to get to the moon, the first astronauts to go to Mars are going to travel for months. In order to travel such large distances, the spacecraft that carry them and their cargo are going to require more efficient propulsion systems than those most commonly used today, which require large amounts of heavy fuel. SEP systems that use xenon gas are lighter and more efficient than chemical engines. But because the travel time required for astronauts going to Mars would be so long, their spacecraft would need to be larger than those used by Apollo astronauts. And because of this, returning them to Earth for refueling would be incredibly difficult and inefficient. Designing the spacecraft to be refueled in-space would allow them to be kept in space and re-used for multiple journeys. The xenon transfer technologies being developed by SSCO on RRM3 make this an architecture option NASA can implement in the future with minimal risk. And xenon is not the only resource that would need replenishment. Liquid cryogens have multiple uses in spaceflight – as a propellant, a coolant, and life support system resource. In all cases, these consumables must be replaced by either replacing the entire system or by replenishing the cryogen. RRM3 is also developing the technologies desired to implement an in-space or planetary serviceable cryogen system in exploration mission architectures. Hypergolics will also most likely remain as the reliable proven method for mission RPO maneuvers and other critical rapid thrust burns, and ground and RRM testing to date has enabled refueling capabilities for both fuel and oxidizer services.

Whether the goal is to rendezvous spacecraft, replenish their resources, or even assemble them in-space, the ability for robotic systems to perform these tasks is essential – human activity in space requires too many resources and carries too much risk to be the primary way to carry out the ambitious architecture outlined above. But just as humans would if they were to perform the work, robots require tools. The RRM payload featured four of the most sophisticated servicing space robotic tools ever created and laid the groundwork for more advanced tools to be created. SSCO is already in work developing these tools – tools that can grab client satellites, perform detailed visual inspections, manipulate hoses and cables, connect leak free to fill drain ports, and more. Developing these tools makes it possible for robotic systems to perform complex operations in space, and that will be a requirement for achieving supportability via in-space servicing.

IV. Conclusion

Debates about the benefits of space exploration have taken place for more than 50 years. As is the case with so many things, the question is not whether the goal is a good one, but rather – is it worth it? Going deeper into space than has been done in the past, to Mars, the asteroids, and beyond is not an easy goal. It will require effort, money, and time. Answering the question of whether that goal is worth those things is easier if it requires less. Less effort. Less money. Less time. For those who advocate for exploring deeper into space, developing concepts and ideas that require less should be the goal. Applying the concept of supportability to those concepts and ideas will achieve that. In-space servicing is an avenue to supportability. Spacecraft that can be refueled in space can be less complex and be used more often. If a vehicle carrying a habitat can be launched separately from a vehicle carrying supplies and those vehicles could autonomously rendezvous on-orbit for a trip to Mars, the work of getting those items to Mars becomes more cost-effective and more efficient. Operators on the ground who can control robots in space, equipped with advanced tools for performing multiple tasks, can save work for astronauts in space or on Mars freeing them up to do more complex work. The technology being developed for in-space servicing tasks is laying the foundation for architecture options meeting supportability in future exploration missions that will reduce the risk, time and cost associated with those missions. Through in-space servicing, supportability can be achieved.

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